Reply to Comment on Strangelets as cosmic rays beyond the GZK-cutoff

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(Dated: October 8, 2003)

PACS numbers: 98.70.Sa, 12.38.Mh, 12.39.Ba, 24.85.+p

In [1] it was demonstrated that strangelets (stable lumps of quark matter) have properties which circumvent both the acceleration problem and the energy-loss problems facing more mundane candidates for ultrahigh energy cosmic rays beyond 10^{20} eV, such as protons and nuclei.

In the preceding Comment Balberg [2] argues that such a galactic flux of ultrahigh energy strangelets would trigger transformation of all neutron stars into strange quark matter stars. He further argues, that all neutron stars can not be strange stars, and therefore finds the scenario in [1] unlikely.

Here I show that the first assumption in [2] is incorrect because strangelets at the relevant energies will be destroyed in collisions with the stars they are supposed to transform. I further argue, that it is not currently known whether all neutron stars are in fact strange stars. Thus the scenario presented in [1] remains viable.

Strangelet fragmentation will occur if the total energy added in inelastic collisions with nuclei exceeds the strangelet binding energy, which can be some tens of MeV per baryon. A strangelet with baryon number A will be destroyed in a single head-on collision with a stellar proton if $E_{\rm col} = 10^{20}{\rm eV}A^{-1}E_{20} > E_{\rm bind} \approx 10^7{\rm eV}AE_{B10}$ or $A < 3\times 10^6 E_{20}^{1/2}E_{B10}^{-1/2}$, where E_{B10} is the binding energy per baryon in units of 10 MeV, and E_{20} is the cosmic ray kinetic energy in units of 10^{20} eV. Bringing a strangelet to rest in the star requires the strangelet to move through a total column of mass roughly equal to its own, i.e. of order A collisions with protons or a fragmentation limit up to $A < 10^{13}E_{20}E_{B10}^{-1}$ (highly charged strangelets will have a scattering cross section larger than geometrical, which can reduce this A-limit somewhat). Smaller strangelet fragments potentially formed in such ultra-relativistic collisions will have the same Lorentz factor and energy per baryon as the original strangelet, and will therefore be prone to destruction in later collisions. While the details of strangelet fragmentation remains to be studied (much of the necessary input physics is poorly known) these order-of-magnitude estimates demonstrate that the ultrahigh energy strangelets discussed in [1] will be destroyed in collisions rather than serve as seeds to transform neutron stars into strange stars.

In contrast to the extremely high energy cosmic ray strangelets, even a small flux of strangelets at low energies would be able to convert all neutron stars into strange stars. This was first shown in detail in [3] and [4] more than a decade ago. At that time it was argued (also by the present author in [3]) that this ruled out the hypothesis of stable strange quark matter and strangelets, because some properties of pulsars (notably the glitch phenomenon) seemed inconsistent with strange star properties. Balberg [2] revives this argument and lists a set of such properties including glitches, r-mode instabilities and cooling. However at the current level of understanding it is premature to rule out strange stars on these grounds. The strange star glitch problem [5] has been shown to be marginally consistent with ordinary strange stars with nuclear crusts [6], and may also find an explanation in the crystalline phases recently discovered in color-superconducting quark matter [7]. The r-mode instabilities that rule out the simplest color-flavor locked strange stars [8] may also be consistent in models with crystalline phases, and similar counterexamples exist for the other effects mentioned in [2]. Summarizing, it is not known at present whether strange stars exist at all, but it is not ruled out either, that all "neutron" stars could be strange stars.

In conclusion, the strangelet scenario for ultrahigh energy cosmic rays presented in [1] remains viable.

This work was supported by the Theoretical Astrophysics Center under the Danish National Research Foundation, and by the Danish Natural Science Research Council.

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